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Measurement Arrangements for Complex Impedances

This article proposes and describes a scheme for measuring reflection coefficients of any load. They are indicated directly as a point on a Smith diagram. In principle one could take the values given by the measurement system and draw them directly on a Smith diagram using an X-Y plotter.

The measured voltages could also be taken to the X and Y inputs (equal sensitivity) of an oscilloscope and represent the locations of the reflection coefficients in real time. Additionally one could fix a transparent Smith diagram (or an enlarged section of one) over the 'scope's CRT.

I have said locations in the plural as it is possible to sweep the frequency - or vary the load - so that a line is drawn instead of just a point. This is an extremely capable tool for aligning circuitry. Fig.1 shows the overall scheme, which is composed in principle of an RF line with four detectors fixed at eighth-wavelength distances. Fig.2 shows a typical measurement result.

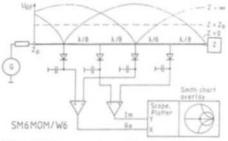


Fig. 1 With two pairs of forwards-current diodes on an RF line, two amplifiers and an RF generator (approx. 1mW) complex reflection coefficients can be represented and measured. Because of the necessary 8th-wavelength distances, the frequency range of this arrangement is restricted: about one octave for antenna alignment: about +/- 5 to 10% around the design frequency for most measurements. Precision measurements can be carried out only at the design frequency.



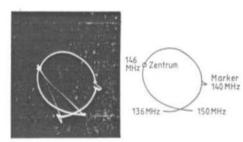


Fig.2 An HB9CV antenna, swept from 136 to 150MHz. Resonance lies at 146MHz (white spot at centre of screen and centre of Smith diagram). The marker on the outer right indicates 140MHz: the antenna is not good at this point.

1.

PRE-HISTORY

Much has already been written about the Smith chart but the fundamental work is - not surprisingly - by Mr Philip H. Smith (1). The measurement instrument used here was calibrated by me in 1986 at a Design Contest and published in (2).

Later at the Foothill fleamarket in San Mateo, California I found a UHF admittance meter made by General Radio: with a receiver as detector it functions superbly. Doubtless there must be literature which I have not found yet for this device.

Finally there was the "Z-g Diagraph" from Rohde & Schwarz which showed some similarity and its description (3) can be read profitably in this connection.

In previous issues of VHF COMMUNICA-TIONS the function and construction of directional couplers (4, 5) and diode detectors (6) have been described (references are to the German edition); these publications give a lot of practical information.

For some decades now the Smith diagram has

been the means by which RF engineers illustrated complex resistances and achieved graphical solutions of matching problems, in other words an enhancement for the slide rule. These days the same problems (with many figures behind the decimal point) are more easily calculated with a computer and it can also represent the results on the screen in the form of a Smith diagram, which completes the circle.

Yet the computer is of little help with an "actual" problem! There on the bench sits a filter which needs aligning, there is an antenna that needs matching, how good is this attenuator or that load? If one could see their reflection coefficients on a Smith chart then one could tell how good or bad they were and what needed doing!

That is the application for this innovation.

Ideas for this came from my excellent tutor Ingvar Svensson at the Engineering Academy in Goeteborg; he treated this theme (like all the others) as a figment of fantasy, as did Magnus Koch, an engineer with whom I was happy to collaborate several years ago. He is a measurement specialist and once said "If you can measure it with a bridge, do so."! I have merely combined the thoughts of these two men!

2.

FUNCTIONAL METHOD

An RF generator G is connected to one end of an RF line and a load Z to the other, the length of the line being at least one wavelength (Fig.1). If the load is equal to the surge impedance of the line Z0 there is no reflection at the load; all power is absorbed in the load and converted to heat. At every position along the line one can measure the same RF voltage, assuming (as we do here) that losses in the measurement line are overlooked.





Fig.3 The UHF Admittance meter by General Radio

If the load is not equal to Z0 part of the power is reflected at the load. If the generator is also not properly matched then part of the reflected power is reflected again by the generator and the relationships become quite complicated. We shall assume that the generator is correctly matched.

The so-called mismatch can arise simply from a 50 ohm line being terminated in a 40 ohm resistor. Equally the termination might have too high a value or combine resistance with some inductance or capacity, either in series or in parallel. There are countless possibilities with mismatches.

Some forms of mismatch produce total reflection, certainly all those which have no resistive component: short circuit, open circuit, capacity, inductance and combinations of these.

If the load is not equal to the impedance of the line, the voltage will not be the same everywhere: instead it will vary periodically, giving us a ''standing wave''. Its form repeats itself every half wavelength along the line.

With a short circuit (or a load smaller than Z0) a voltage minimum and current maximum appears that the load end of the line. With an open circuit the opposite applies. Capacitive and inductive components lie in between.

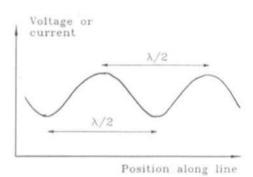


Fig.4 Voltage or current function along a line with a badly matched load

When the reflection is pronounced - close to total reflection -the minima are sharp and drop nearly to zero volts. In significant cases of mismatching - as with a standing wave ratio (SWR) of 2 - the voltage variation along the line looks almost like a sine wave (Fig.4). With a perfect match there are, as mentioned, no periodic variations and at most a drop in potential if the measurement line has sufficient attenuation.

If one now measures the voltage on the RF line at four points each spaced an eighth-wavelength (45 degrees) apart, the four voltages should relate to one another in a sine/cosine fashion if there is a standing wave present. The four voltages are summed in pairs -without amplification to a resistor or at the output of a differential amplifier - and taken to the X and Y inputs of a plotter or oscilloscope.

If you now consider some extreme cases of terminations and work through the voltage relations resulting from them (Fig.1), you will quickly understand the arrangement and how you can use it.

We shall take a resonant circuit which at resonance gives rise to total reflection (Fig.5). The coil should be small and the (variable) capacitor screened, so that little radiation



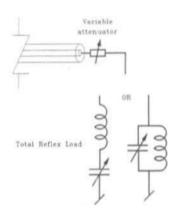


Fig.5 How calibration is carried out

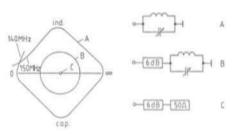


Fig.6 Three different terminations: A, B, C and the resulting indications here for a measured frequency of 145MHz

occurs and as much power as possible is reflected. A (variable) attenuator ahead of the resonant circuit delivers calibration values.

A perfectly matched load (50 ohm instrumentation termination or attenuator of at least 30dB) gives the same voltage on each of the four diodes, everything is symmetrical and on the display we get a point in the centre of the Smith diagram.

With a resonant circuit at resonance used as load we get maximum asymmetry of the voltages of each pair and the point indicated moves out to the right (parallel circuit, infinity) or out to the left (series circuit, short circuit). If we tune the resonance (variable capacitor), the measurement point will wander around the periphery of the Smith diagram. The area around the short circuit (outer left) will remain clear with a parallel circuit as will the area around infinity (outer right) for a series circuit.

In reality we have not a circle but a square with rounded corners standing on one of these corners. This is because the voltages which determine the measured points do not have a sine wave form but pronounced minima. However, the better the match, the closer the shape is to a circle because the voltage response is nearer a sine wave (Fig.6).

If we now place a 3dB attenuator in front of the resonant circuit and tune it once more, the measured point now shows as a concentric, nearly round circle for 6dB return loss. With a 6dB attenuator we get a circle for 12dB return loss attenuation and with a 10dB one we have the circle for 20dB.

With an attenuator of, say, 10dB permanently on the output of the RF line the detector arrangement "sees" a return loss of at least 20dB, regardless of whatever is connected afterwards to be measured. This detracts from the appearance of sharp voltage minima and the diagram produced in this way will always be nice and round. If absolute sensitivity is required for specific measurements the attenuator should be taken out and you will have a 20dB enhanced measurement range. If the item being measured has a good match the diagram produced will be round in any case.

2.1 Operation

When we described the function of the detector arrangement previously we already mentioned the importance of calibration with the help of resonant circuits and attenuators. Practical use for the measurement of unknown impedances is not far removed from this.

First there must be a generator and measure-



ment set-up for the frequency in question. The actual measurement involves comparing the display created by the item under examination with those given by the resonant circuit and attenuators.

The measurement arrangement is extremely sensitive so that even very long RF cables with measurable attenuation (which would otherwise have to be avoided) can be used without problem. Let us take for example a 30 metre length of RG-58 and measure it at 145MHz. The cable is 14.5 wavelengths long - that is 29 half-wavelengths. By varying the frequency by half of 1/29th of 145MHz (plus or minus 2.5MHz) we find out that the measurement points indicated describe a complete circle on the Smith diagram!

In this way it is possible to measure a remote object, for instance an antenna on the roof. This is the way it is done:

The antenna cable is first separated from the feed-point of the antenna and left open-circuit. Then we add lengths bit by bit at the accessible end of the cable until the display on the oscilloscope is out to the right, as for a parallel circuit in resonance. Instead of lengthening the cable one can also practise a small amount of frequency variation, as described in a previous section. Now we climb on the roof once more and connect up the antenna to be measured. Back downstairs we can see the complex reflection coefficients of the antenna and reflect on what is to be done (if anything at all is to be done). Or we can just sit and watch the 'scope display, noting when vultures come in and land on the antenna ...

In order to determine the amount of mismatching we use the arrangement in Fig.5. The value of the attenuator is varied until the amount (that is, the distance indicated from the centre of the display) is as great as that caused by the antenna. Then we double the value of attenuation engraved on the attenuator and that is the return loss of our antenna! Given the opportunity we can also measure the attenuation of the feeder cable. If the roof end of the cable is open, total reflection occurs. Connecting the RF line we now have a signal travelling the length of the antenna cable twice and then being displayed (slightly) smaller as a total reflection. By adjusting the calibration according to Fig5 to give the same indication we learn the attenuation of the cable. This is directly equivalent to the attenuation read off, as in this case the wave also travels twice through the calibration set-up.

3.

CONSTRUCTION

The measurement apparatus is made up fundamentally from a piece of RF line, four detectors and an indicating unit. My standard circuit is shown in Fig.7. According to frequency range and materials available, many widely-differing versions can be envisaged. Construction must follow good RF

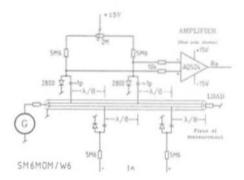


Fig.7 Circuit of the measurement bridge (second amplifier not drawn); in the arrangement shown the upper amplifier delivers the measured voltage of the actual component, the lower that of the imaginary component. Compare with Fig.1



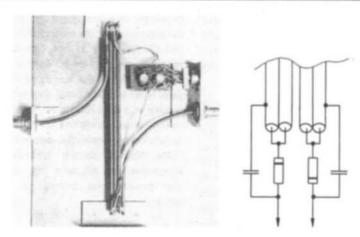


Fig.8 One of my first designs for the 2 metre band: diodes electrically connected and connected in anti-phase. On the right-hand side 8th-wave length pieces of semi-rigid cable next to one another

practice appropriate for the band in question of course and, in order to obtain repeatable measurements, it must be mechanically stable.

For each of the elements mentioned I will provide some information.

3.1 RF Line.

The RF line can be coaxial or take the form of stripline or micro-stripline, it can be parallel lines or waveguide. It only has to suit the use envisaged for it and be mechanically stable.

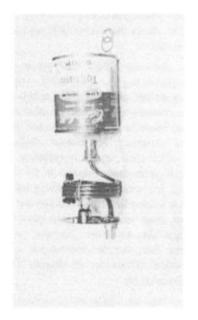
In most cases constructors will go for coaxial cable, and for the VHF, UHF and SHF bands a semi-rigid copper-sheathed cable represents a very good choice. The technique is not restricted to 50 ohms: for television we can take 75 ohm cable and for specialised measurement systems with an impedance of 25, 16.6 or 12.5 ohms for example we can use two, three or four lengths of 50 ohm cable in parallel. The detectors are then connected to only one of the cables.

For frequencies below 30MHz RG-58 or RG-8 is fine: for 7MHz an eighth-wavelength is 3.5 metres long, which is still more or less manageable.

The pieces of cable can be laid beside one another as in Fig.8. For 145MHz as an example the eighth-wavelength pieces are 170 to 224mm long, according to the cable dielectric. Two of the detectors are each above and below: the small bumps caused by them are cancelled out because they affect the four quadrants of the Smith diagram to an equal extent. I always choose the blocking capacitors so that they are in series resonance at the frequency measured: for example at two metres 150pF with 15 to 20mm lead length.

A more elegant method is to coil (semi-rigid) cable, as shown in Fig.9. Each turn is an eighth-wavelength long, so that V:F7 all four diodes lie alongside one another. While the diodes cannot be made out,in the picture, you can see the black blocking capacitors. The measured voltages are led to a DIN connector. In a separate case there are two multi-turn trimpots for balancing and summing; their wipers are connected to two op-amps of the type LM351.





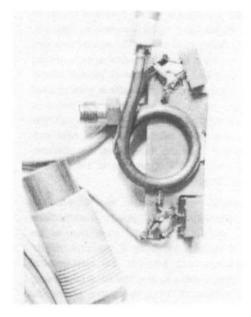


Fig.9(left) A subsequent version (for 145MHz) with coiled copper-sheathed cable, 8th-wavelenth per turn, all four diodes on one side. A soup tin completes the arrangement mechanically

Fig.10(right) A version for antenna measurements in the 915MHz region; at higher powers used without amplifier. Each of the two turns is a quarter-wavelength

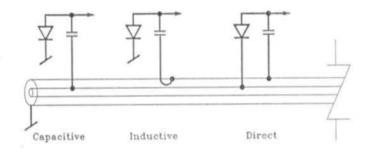


Fig.11 Three ways of coupling the detector diode to the RF line



Fig.10 shows a version for 915MHz. An eighth-wavelength here is only half a turn, so the diodes have to be mounted on opposite sides facing each other. The second turn and the two other diodes are out of sight below the screen panel (sheet brass or printed circuit board material), which makes a good ground plane. As an RF connector the SMA is particularly suitable; the measured voltages are once more measured in two multi-turn pots and summed, then taken via screened cable and a DIN connector to the separate amplifier box.

Naturally you can also use stripline or micro-stripline. In this form it is particularly easy to tailor the surge impedance to the application. In particular if you leave off the connectors and integrate the measurement set-up into one unit, you have some interesting possibilities. At lower frequencies the lengths involved could present difficulties.

3.2 Detectors

Either the electrical field can be coupled off the line with a capacitor or the magnetic field via a coupling loop; as Fig.11 indicates, at very low levels one can also make a direct electrical connection to the line. On the other hand, at very high RF power levels it is only necessary to place the diodes in the vicinity of the RF line.

In my first research set-ups I soldered the diodes direct to the centre conductor of the line, but this was not a good idea. For the rectified current there must always be a DC return path somewhere, and with the IC-202 I had problems with the direct current on the antenna input. It is better to connect the diodes to ground on one side and connect the other end loosely to the line via a capacitor, as shown in Fig.7.

Fig.7 also shows how to provide conventional Schottky diodes (e.g. HP2800) with bias current for achieving maximum sensitivity. At the same time you can balance the diode pairs. In this way I have achieved good results up to 1300 MHz: above this the HP2800 appears to fall off rapidly.

For the short-wave and VHF bands germanium diodes (e.g. AA118, 1N34) - without bias - are no bad choice. For the middle and upper microwave regions, one the other hand, one must resort to the expensive and in all respects sensitive low-barrier Schottky diodes, which also require no biassing. The old silicon point-contact diodes of the 1N21 and 1N23 etc. series are also quite good, but they must be handled like MOS devices. For matching them beforehand, they should be first short-circuited, then clamped to the measuring line, then the short-circuit removed. Detailed information on detector diodes will be found in (6).

Initially I had the diodes in pairs connected head-to-tail, to read the differential voltage direct. At medium and high RF power levels it is then easy to connect them direct to the X and Y inputs of a plotter or oscilloscope or even to meters. But then the arrangement shown in Fig.7 turned out to be easy to copy and sensitive as well.

Fundamentally it is a good idea to pair the diodes. You can use a conventional digital multimeter: in the 200k-ohms range there is generally 10uA flowing; one reads the voltage drop in the direction of current flow and selects the diodes which are most similar.

3.3 Indication of measured values

For displaying the test results there is again a range of possibilities. One can use two test instruments having a centre zero position; one shows the real component, the other the imaginary component of the reflection coefficient.

One can also take an instrument with two movements and crossed-needles display, in

(4)

which case the cross-over point will indicate somewhat coarsely of course - the location of the reflection coefficient on the Smith chart. One could bring into use a mirror galvanometer or servo motors with a mirror to cast a bright spot onto a large Smith chart on the wall (perhaps with HeNe laser for classroom use?). And finally you have the XY plotter or oscilloscope in XY mode already mentioned several times. Both can be very sensitive and offer adequate adjustment range for calibrating the display field.

3.4 Concluding remarks

For a broad range of applications and frequency bands it will be necessary to construct a series of measuring set-ups of various dimensions. It is not necessary, however, to equip each one with amplifiers and display components.

The user will do well to equip each detector unit with a four-core screened cable for connection to the amplifier module. For this I use normal audio plugs and sockets. All diodes can then be connected individually to one of the four pins; one resistor each of a few Kohms together with the capacity of the cable acts as a low-pass filter to stop RF interference from reaching the amplifier. The bias resistors and trimmer potentiometers are found in the amplifier unit. The full sensitivity will probably be seldom required possibly for matching measurements at the inputs of receivers or when one wants to employ the motion detector scheme described.

For matching sensitivity to the measurement task you have at your disposal not only the output level of the generator but also the extent to which the diodes are coupled and the gain of the operational amplifiers. Expensive instrumentation amplifiers (e.g. AD524) can easily be pre-set to gain values of 1, 10, 100 or 1000.

[Text adapted by Robert E. Lentz, DL3WR.]

LITERATURE

4.

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The Author's shack!